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APPLICATION FOR LETTERS PATENT
OF THE UNITED STATES

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TITLE OF INVENTION: **Method And Apparatus For Aerial Image
Improvements In Projection Lithography
Using A Phase Shifting Aperture**

TO WHOM IT MAY CONCERN, THE FOLLOWING IS
A SPECIFICATION OF THE AFORESAID INVENTION

**Method and Apparatus for Aerial Image Improvement in Projection
Lithography Using a Phase Shifting Aperture**

5 TECHNICAL FIELD OF THE INVENTION

This invention relates generally to photolithography for semiconductor fabrication and more particularly to aerial image improvement in projection lithography using phase shifting to produce incoherent light to reduce the effects 10 resulting from side maxima formation.

BACKGROUND OF THE INVENTION

As semiconductor feature sizes continue to shrink into the sub-micron 15 range, the effects of light diffraction during photolithographic processes become more pronounced. Common ultraviolet (UV) exposure tools use light sources having a 193, 248, or 365 nm wavelength. When such tools are used to form semiconductor devices having feature sizes of 70 to 350 nm, the effects of light diffraction become quite pronounced and produce interference that affect printed 20 patterns on the semiconductor device.

One area where interference effects are particularly problematic is with patterns that are placed orthogonally to each other. The interference effects tend to degrade the aerial image, thus limiting the resolution and the photolithography process window. The effects of interference can be seen especially at the edges 25 of array type patterns where lines tend to merge or fall over in these regions more easily. In particular, the interference effects appear as side maxima in the printing of the patterns on a semiconductor wafer, which adversely affect the resolution of printed pattern.

There are prior art solutions that use various methods to improve overall resolution of patterns. Some of the prior art solutions utilize off-axis illumination or phase shifting masks. Off-axis illumination will increase overall resolution by re-focusing some of the light rays that are generally diffracted outside of the line

5 of projection. Phase shifting masks shift the phase of a light beam to produce incoherent light where there is a phase difference between different features. The resolution of features is thus improved. However, the present invention improves the lithographic imaging quality of orthogonally oriented features beyond that which is accomplished by applying only the prior art solutions

10 mentioned above. The present invention consists of a less costly solution that is simple and requires no change to existing photolithographic optics or equipment.

SUMMARY OF THE INVENTION

A cost efficient and simple solution for improving the lithographic imaging

- 5 quality of orthogonally oriented features is achieved by preferred embodiments of the present invention having a plate having light transmissive regions which provide phase shifting resulting in improved image quality. In one preferred embodiment the plate comprises a first opaque region located at the center of the plate and a second opaque region formed at the outer edge of the plate. The
- 10 first and second opaque regions define an annular region therebetween. The annular region is light transmissive and comprises a first light transmissive area that imparts a first phase shift to light passing therethrough and a second light transmissive area, which imparts a second phase shift to light passing therethrough.
- 15 The present invention also discloses a method of photolithographically imposing a pattern on a semiconductor wafer, comprising the steps of coating the wafer with a resist layer, providing a coherent light illumination source, and deriving incoherent light from the illumination source by passing light from the illumination source through an aperture having an opaque region in its center and having a first light transmissive area that imparts a first phase shift on light passing therethrough and a second light transmissive area that imparts a second phase shift on light passing therethrough. The method further includes the steps of passing the incoherent light through a photomask
- 20

having a pattern formed thereon and illuminating the resist layer with the incoherent light after the incoherent light has passed through the photomask.

One advantage of the preferred embodiment of the present invention is that it provides a less costly solution to improving the resolution of orthogonally 5 oriented features.

Another advantage of the present invention is that it requires no change to existing photolithographic optics.

BRIEF DESCRIPTION OF THE DRAWINGS

The above features of the present invention will be more clearly understood from consideration of the following descriptions in connection with accompanying drawings in which:

- 5 Figure 1 illustrates a prior art apparatus for photolithographically forming patterned features on the surface of a substrate;
- Figure 2a illustrates exemplary photomask features;
- Figures 2b and 2c illustrate light diffraction and the resulting side maxima;
- Figure 3 illustrates a first preferred embodiment of the present invention;
- 10 Figure 4 shows a system for photolithographically forming patterned features on the surface of a substrate utilizing a preferred embodiment of the present invention;
- Figures 5a and 5b illustrate pattern gratings for pattern features;
- Figure 6 illustrates the intensity profiles with side maxima and coherent
- 15 and incoherent overlap; and
- Figures 7 and 8 are other preferred embodiments of the present invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The making and use of the various embodiments are discussed below in detail. However, it should be appreciated that the present invention provides many 5 applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use the invention, and do not limit the scope of the invention.

Figure 1 illustrates a prior art photolithographic apparatus 10. The apparatus comprises a light source 2, a photomask 8, a focusing lens 9, and a 10 photosensitive layer (a photoresist layer) 4 formed on a semiconductor wafer 6 or similar substrate. Patterns are formed on photoresist layer 4 by passing light from light source 2 through a photomask 8 upon which is formed the pattern desired to be transferred. The light also passes through focusing lens 9 prior to impinging upon layer 4. The light that passes through the photomask 8, 15 however, is subject to interference effects which result in diffraction of the light rays 13 originating at the light source 2.

When the light source 2 illuminates the photomask 8, a circular pattern of illumination is formed on the top plane 17 of the photomask 8. This circular pattern is shown in a top down view of the top plane 17 in Figure 2a. For 20 orthogonal features, the light rays that lie parallel to the axis 22 will define those features such as first feature 24. Light rays that lie parallel to the axis 26 will define features such as second feature 28 which are perpendicular to first feature 24. When the light source 2 illuminates the photomask 8, however, the light rays passing from the photomask which define first and second features 24, 28 on the

photomask may be diffracted, as shown in Figure 2b. The symbol m represents the order of diffraction. An order of zero represents no diffraction and partly diffracted orders are represented by increments along the x-axis (the increments are designated positive and negative to reference their position relative to the y-axis). The diffraction of the light rays result in side maxima 15 having a given intensity as shown in Figure 2c. The side maxima 15 will decrease the resolution by degrading the contrast of the desired pattern. Furthermore, when the side maxima 15 of first and second features 24 and 28 on the photomask 8 overlap, the side maxima 15 add together coherently which further degrades the contrast of the desired pattern.

Figure 3 illustrates a first preferred embodiment of the aperture of the present invention which decreases the effects of overlapping side maxima resulting from the diffraction of light. A plate 50 for aerial image improvement has a substantially circular shape and an outer edge 52. The plate may be made of, but is not limited to, quartz glass. The plate 50 includes a first opaque region 54 having a substantially circular shape located at the center of the plate 50. A second opaque region 56 is formed between the first opaque region 54 of the plate 50 and the outer edge 52 of the plate 50. An annular region 58 is formed around the plate 50 by the first opaque region 54 and second opaque region 56.

The annular region 58 is divided into a first, second, third, and fourth sector 60, 62, 64, and 66, respectively. These light transmissive sectors are formed by varying the thickness of the aperture material which will impart the desired phase shifts as described below.

The first and second sectors 60, 62, respectively, are located opposite from each other and are preferably substantially vertically oriented. Sectors 60, 62 have a thickness, t_1 , and are designed to impart a first phase shift Θ_1 to light passing through first and second sectors 60, 62. The third and fourth sectors 64, 66, respectively, are also located opposite each other and are preferably substantially horizontally oriented. The third and fourth sectors 64, 66 have a second thickness, t_2 , and impart a second phase shift Θ_2 to the light passing through these sectors. The first phase shift Θ_1 is not equal to the second phase shift, which results in a phase difference Θ_Δ . The phase difference Θ_Δ is preferably in the range of $45^\circ - 315^\circ$ and more preferably about 180° . It should be appreciated by those skilled in the art that the phase difference Θ_Δ may be adjusted as necessary to produce the best resolution.

In the preferred embodiment, thicknesses t_1 and t_2 are in the order of 0.1 mm up to 1.0 mm with a thickness difference $\text{abs}(t_1 - t_2)$ equal to $1/(2n_{\text{ref}})$ wavelengths of the light emanating from illumination source 2 (n_{ref} is the refractive index of the material used for the plate 50). In this way, the preferred phase shift difference Θ_Δ is imparted to light passing through sectors 60, 62 relative to sectors 64, 66.

In operation, the preferred embodiment of the present invention is implemented as an aperture 50 in the apparatus shown in Figure 4. The aperture 50 provides off-axis illumination. In off-axis illumination, n th order light rays, both positive and negative, are utilized to improve resolution of pattern features. Note that light rays 13 being in and close to the y -axis are blocked by

opaque region 54 of aperture 50. Light rays closer to the outer edge 52 (as shown in Figure 3) of the aperture 50 are also blocked by ring-shaped opaque

region 56 of aperture 50. Only light rays passing through annular region 58, comprised of sectors 60, 62, 64, and 66, pass through to impinging upon

5 photomask 8. These light rays impinge upon photomask 8 at an angle, as shown. By illuminating the photomask 8 at an angle σ off the y-axis , light rays,

which are usually diffracted outside of the focusing lens 9, pass through the aperture 130 to the focusing lens 9. Note that by using an annular opening region 58, off axis illumination is provided for any feature on photomask 8,

10 regardless of the orientation of that feature (i.e. vertical, horizontal, or at an angle to the vertical or horizontal). The annular region 58 of the aperture 130 results in the improved resolution of any orthogonal features because both positive and negative nth order light rays in any direction around the annular region will be captured by the focusing lens 9.

15 While the resolution is improved by capturing the diffracted light in the annular region 58, the resolution between orthogonal features can be further improved. The phase difference Θ_{Δ} introduced by the four sectors 60, 62, 64, and 66 as described above provides improved resolution to the orthogonal lines by having the intensities of the light passing through the different features of the

20 photomask 8 incoherently overlap. For coherent object illumination all points in the object have wave amplitudes with fixed phase relationships. When the phases vary independently from point to point, the illumination is incoherent. By introducing the phase difference Θ_{Δ} , the light illumination becomes incoherent

and the resolution is further improved by reduction of the affects of the side maxima formation as described below.

Figure 6 illustrates the light intensity profiles with overlapping side maxima for features illuminated with coherent light and incoherent light. A first intensity

5 profile is represented by line 120. Line 120 represents the light intensity of mask feature in a horizontal direction, such as feature 104 of Figure 5a. Line 122

represents the intensity profile of vertical mask feature, such as feature 110 of

Figure 5b. One skilled in the art will recognize that in actual practice, both

feature 104 and feature 110 will be formed on the same photomask. The

10 distortion or side maxima which results in degrading the contrast of the image (here, the contrast between orthogonal lines) is represented by lines 124 and 126.

The side maxima overlap in a naturally coherent fashion. In other words the light wave characteristics are the same for both of the features (horizontal and vertical). The coherent overlap is represented by line 124. Mathematically,

15 the overlap intensity $\propto (E_1 + E_2)^2$, where E represents the amplitude of the electrical field of the light wave.

When the present invention is utilized, by imposing a phase shift between light that is refracted in the substantially vertical direction and light that is refracted in the substantially horizontal direction, the side maxima for such

20 vertical and horizontally oriented features overlap in an incoherent fashion, as represented by line 126. As evident from the figure, the side maxima is

significantly smaller, thus the resolution is significantly improved. The incoherent overlap is equal to $I_1 + I_2 \propto (E_1^2 + E_2^2)$. Thus, the light intensity in those regions

where the side maxima overlap is decreased, although not eliminated, to improve contrast and provide improved resolution.

Further detail regarding the design and manufacture of the preferred embodiment apertures is now provided. As discussed above, aperture 50 is

- 5 preferably formed of quartz glass, although other optical quality materials with similar optical characteristics could be substituted. Preferably the aperture is nominally between 0.01 cm to 0.1 cm in thickness and typically between 0.3 and 3 cm in diameter. Opaque regions 54 and 56 are preferably formed by coating a top surface of plate 50 with a thin coating of chromium or other well known light
- 10 blocking films, and patterning the coating using well known photolithographic techniques.

The sectors 60, 62, 64, and 66 are preferably formed by grinding plate 50 to the desired thickness using mechanical polishing or etching techniques.

Alternatively, the sectors can be built up to a desired thickness by using an

- 15 optically compatible coating. In the preferred embodiments the sectors 60, 62, 64, and 66 are formed by etching techniques.

Figure 7 illustrates another preferred embodiment of the present invention.

Figure 7 shows a plate 128 that includes a substantially circular first opaque

region 130 located in the center of the plate 128 and a second opaque region

- 20 132 located along the diameter of the outer edge 134 of the plate 128. The first and second opaque regions 130, 132 form an annular opening 136. Within the annular opening 136 is formed four opaque sectors 138 alternately placed between four light transmissive sectors 140. Each of the four opaque sectors

138 has a first and a second edge 142 and 144, respectively. The first edge 142 of each opaque sector 138 is formed by the first edge 146 of the annular opening 136. The second edge 144 of each opaque sector 138 is seamlessly integrated into the second opaque sector 132. The third and fourth edges 148 and 150, 5 respectively, of the four opaque sectors 138 form the adjacent edges of the four light transmissive sectors 140.

In this case, the light transmissive sectors 140 of the aperture located opposite of each other have the *same* plate thickness, and neighboring transmissive sectors have plates with a thickness *difference* equal to $1/(2n_{ref})$

10 wavelengths of the light emanating from illumination source 2 (n_{ref} is the refractive index of the material used for the plate 128)

Another embodiment of the present invention is shown in Figure 8. In this embodiment, instead of ring segment openings, such as the sectors 140, circular openings 150 are used to accomplish the off-axis illumination. The material 15 thickness of the circular openings are similar to the material thickness of the ring segment openings as discussed above.

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as 20 other embodiments of the invention, will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.